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U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

The Practical Uses of AC-DC Transfer Instruments

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Earl S. Williams

ABSTRACT

Alternating currents and voltages are measured most accurately at this time when they are compared with nominally equal and known dc currents and voltages. The comparisons are usually made with thermal transfer instruments which respond nearly equally to ac and dc quantities. Practical information and recommended procedures are given for using these instruments along with diagrams of apparatus and examples of typical data and calculations. Methods for minimizing difficulties caused by dc reversal differences, thermal drift, energy picked up from local electromagnetic fields, and the deviation from square-law response of these instruments are considered. Causes of ac-dc differences are discussed, and methods for measuring them and applying corrections are also described.

Key words: ac current measurements; ac voltage measurements; ac-dc comparator; ac-dc difference; thermoelement.

1.0 Introduction

The basic units for electrical measurements are derived at the National Bureau of Standards in absolute terms from the units of mass, length, and time. The standards primarily used to transfer these units for direct current measurements from NBS to other users, and to preserve them in the standards laboratories, are the saturated standard cell (the volt) and the standard resistor. With these and a variety of shunts and resistance ratio instruments for range extension, direct current and voltage can be measured with high accuracy.

Since there is no ac counterpart to the standard cell, measurements of alternating current, voltage, and power are made relative to these same standards. The chain of measurements is extended to these alternating quantities by ac-dc transfer instruments, which have a flat and known frequency response and hence may be calibrated on direct current and then used for alternating current measurements. They provide an accurate transfer from direct voltage and current standards to alternating current and voltage measurements, hence the name.

Electrodynamic instruments have been used to transfer voltage, current, and power; however, they are limited in frequency to a few thousand hertz due to their relatively high inductance. Electrostatic moving systems are usable to higher frequencies, but they have severe low voltage limitations. Instruments which respond to peak and average values of ac voltage have been employed successfully over certain voltage and frequency ranges (see section 3.8). The instruments most widely used for voltage and current transfer measurements, and the ones to be discussed here, are electrothermal. They are usually called thermal voltage converters (TVCs) and thermal current converters (TCCs) to distinguish them from other types of transfer instruments [1].

2.0 Thermoelements

The key component in these transfer instruments is a thermoelement (TE), consisting of a heater which carries the current to be measured and a thermocouple attached to its midpoint. The output from the thermocouple is relatively low (7 to 12 mV); however, heater current differences, and differences between ac and dc currents, as small as one part-per-million (ppm) can be detected, if changes in the output are monitored with a sensitive detector--a galvanometer or microvoltmeter. Thermoelements for currents from 1 to 1000 mA are available with evacuated glass-bulb enclosures and with insulation (a small ceramic bead) between the thermocouple and heater (fig. 1). TEs are available for currents up to at least 20 amperes, but vacuum enclosures are not feasible at these currents because the elements require heavy copper conductors which are very difficult to pass through a vacuum seal. Insulation is not generally available in TEs for currents greater than one ampere. They are difficult to construct, and the demand for them is not great. Most current comparisons are made with special ac shunts in parallel with low-range TEs (see section 8).

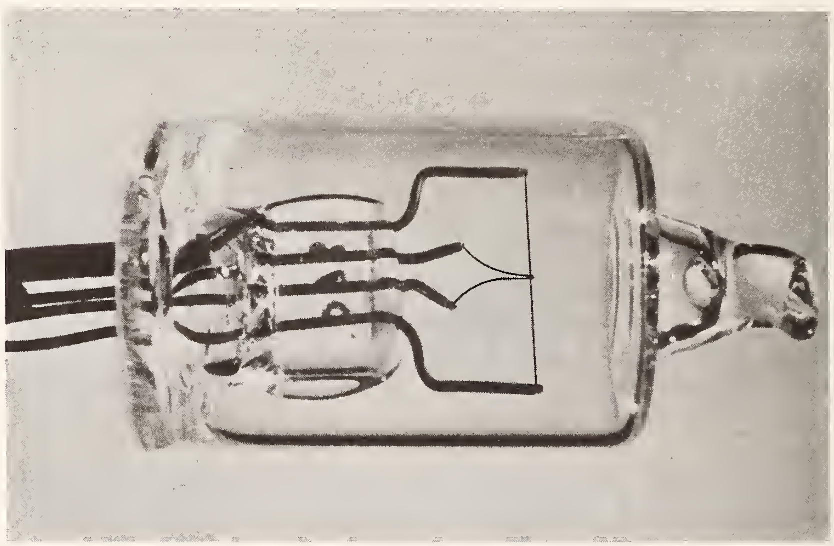

Figure 1. Vacuum thermoelement. (Heater and thermocouple wires retouched.)

The TE heater is short and straight thus having minimal reactance, and the insulation of the thermoelement prevents any appreciable interaction between the ac current and the read-out instrument. TEs are therefore well suited to measurements at audio and higher frequencies. They are used with series resistors in multirange TVCs up to 100 kHz on most ranges and to 1 or 2 MHz at low voltages. Single-range units with carbon or metal film resistors coaxially mounted in tubular casings are used up to 100 MHz.

Multijunction thermoelements [2,3,4,5], with a relatively low heater temperature and 50 to 200 thermocouples in series distributed evenly along the heater, are capable of higher accuracy in transfer measurements, and their structure minimizes most of the thermoelectric effects that cause errors in

other types of TEs. However, they are difficult to construct, and therefore expensive and not readily available.

2.1 Output Characteristics

The thermocouple output of the TE is a function of the power dissipated in the heater, and therefore varies approximately as the square of the heater current. However, the device does deviate significantly from a square-law response as the heater current approaches the rated value. The relationship of the output, E, to the heater current, I, may be expressed as

$$E = kI^n. \tag{1}$$

The response appears to be nearly square-law (i.e., n=2) at very low currents, but n is usually 1.6 to 1.9 at rated heater current. The factor k varies somewhat with large changes in heater current, but this is not a constraint. The TE is a substitution device, and not normally used to measure ac current as a function of thermocouple output. The factor k is constant over a narrow range where nearly equal ac and dc currents are compared.

The relationship between a small change in TE heater current (ΔI) and the corresponding change in output (ΔE) is expressed as

$$\Delta I/I = \Delta E/nE. \tag{2}$$

If the thermoelement is in a TVC,

$$\Delta V/V = \Delta E/nE. \tag{3}$$

It is often advantageous to make measurements of n and use the data in calculations as suggested in sections 3.2 and 6.2. The measurements are not difficult, and the values are quite permanent. Methods for measuring n are described in section 7.

2.2 DC Reversal Difference

DC reversal difference is generally (and in this document) defined as the percentage difference between the dc current and its reversed counterpart, when they both produce the same output from a TE. This difference is not necessarily constant and may increase in some TEs as the heater current is lowered. A low dc reversal difference is, of course, advantageous. The difference between ac and dc voltage and current is often measured by observing the change in indication of an instrument which responds to changes in TE output as ac and dc are applied. If the dc reversal difference is large, it may be necessary to reduce the sensitivity of the read-out instrument to keep all readings on scale.

It is recommended that both directions of dc be used in the procedures described here. However, it is not often necessary to have an explicit measurement of dc reversal difference. A measurement may be desirable sometimes, as for instance when making sure that new TEs conform to specifications. A low-range TE can be connected in series with a resistance of 50 to 200 kΩ, and the appropriate voltage applied for rated heater current. The value of the two direct voltages which give equal output can be read from a

calibrated source or measured with a digital voltmeter. Common current-measuring equipment, usually a potentiometer or a digital voltmeter and a shunt, is used to measure currents in higher range TEs. In any method, it is advisable to use a test sequence which will minimize the effect of drift in the TE output. Readings should be taken with DC+, DC-, DC+ after time intervals which are about equal. The average of values obtained with the two positive dc voltages should be used in the calculations.

DC reversal difference can also be measured conveniently with a second or reference TE of about the same range and with known n values. The two heaters are connected in series through a switch which reverses the test TE input but not that of the reference one (fig. 2). Direct and reversed currents are adjusted for equal output from the test TE (null on detector D1). The emf of the reference TE (E) is read from its potentiometer (Pot'r) and changes in emf (ΔE) are computed from readings taken from the detector (D2), which must be a microvoltmeter or a calibrated galvanometer. DC reversal difference, $\Delta I/I$, is then computed from eq. (2).

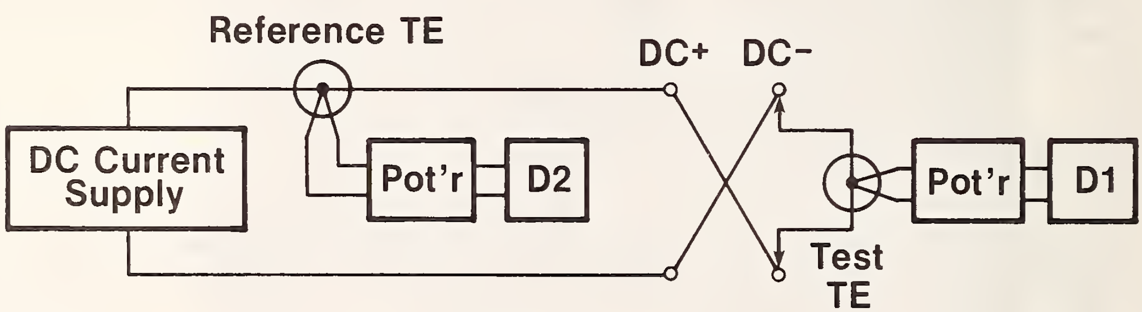

Figure 2. Circuits for dc reversal difference measurements.

As pointed out in the previous section, a TE output varies approximately as the square of the heater current. If dc reversal difference were to be defined as the percentage difference between emfs obtained with equal currents in opposite directions, the figure would be about twice as large.

DC reversal differences range from near zero to several hundredths of a percent. They are largely due to Peltier heating and cooling at the ends of the heater, and to Thomson heating in the two halves of the heater [6,7]. Both of these effects cause asymmetry in the temperature rise of the heater. The asymmetry is affected when the current is reversed, and therefore the temperature at the point where the thermocouple is attached is changed. DC reversal difference is minimized by placing the thermocouple at the thermal center of the heater. If the heater wire is not quite uniform, this may not be the exact mechanical center. DC reversal difference is therefore not easily controlled. Some manufacturers sort TEs according to dc reversal difference and market those with low dc reversal difference as a premium product.

DC reversal difference rarely changes with use, and the few changes that have been observed are believed to be due to the heater having been overloaded. One possible explanation for this is that one-half of the heater was stressed more than the other, and its thermal center was shifted relative to the thermocouple's position. If this model is correct, the dc reversal difference could be either increased or decreased by an overload.

2.3 Temperature Coefficient

The temperature coefficient of most TEs (percentage change in output for a temperature change of 1 °C with constant heater current) is relatively high--often 0.1%/°C. Elements should therefore be mounted in a thermally lagged enclosure to minimize the effect of ambient temperature changes. The output of a TE can be very stable at a fixed temperature if the heater is carrying a constant current for several hours. However, if the instrument is switched back and forth between ac and dc after a brief warm up, as it is in most measurements, the output will usually drift. The drift may be negligible during the short time required for a measurement, especially at low voltages. However, on many ranges where there is some self-heating effect, the drift rate is apt to be quite constant but significant. Accurate and consistent measurements can be made under these circumstances, if readings are taken at time intervals that are about equal and in a sequence which tends to average out the effect of drift (e.g., [a] +DC, AC, -DC or [b] AC, +DC, -DC, AC).

2.4 AC-DC Difference

Thermoelements, as well as TVCs and TCCs, sometimes have a significant ac-dc difference, δ, particularly at higher frequencies,

$$\delta = (V_a - V_d)/V_d ,$$

where V_a and V_d are the ac voltage and the average of the two directions of dc voltage required for equal response, or output emf. For voltage measurements,

$$V_a = V_d (1 + \delta). \tag{4}$$

Similarily, for current converters, $I_a = I_d (1 + \delta)$.

AC-dc differences, methods for measuring them, and the application of corrections are discussed in sections 5.0 to 6.5.

2.5 Radio Frequency Interference

Thermoelements have a frequency response which extends to 100 MHz or more, and measurements made with them can therefore be affected by local electromagnetic fields. Interference from television stations can be particularly troublesome with low-current TEs, because the length of leads used in calibration laboratories often makes them an effective antenna. Energy picked up by a measurement circuit can usually be detected by shorting the TVC input terminals with all connections in place as in normal use, but with the power supplies off. Any change in the indication of a detector in the TVC output circuit as the short is opened and closed will indicate a pick up problem. Interference can usually be avoided by using coaxial leads and shielded circuit components. In extreme cases it may be necessary to work in a shielded room.

3.0 Voltage Measurements

AC voltage is measured most accurately at this time by comparison with a nominally equal dc reference voltage using a thermal voltage converter. The TVC may consist simply of a series resistor and a thermoelement mounted coaxially in a tubular casing, usually a plated brass tube, with input and output connectors [8]. As noted earlier, this configuration is well suited to rf measurements. In another arrangement, the resistor is mounted in one tube and the TE in another. The TE can then be attached to any one of a set of resistors to make a TVC with the desired voltage range [9]. The number of resistors in a set can be reduced to about half, by using two TEs with different current ratings (e.g., 2.5 and 5 mA). Each resistor is then used for two ranges [10]. These sets, which are commercially available, have two distinct advantages. The ac-dc difference corrections are very small, and they can be determined relative to any one range, which has known corrections, by a step-up or step-down intercomparison of adjacent ranges.

Multirange TVCs usually contain 10 to 14 ranges between 0.5 and 1000 volts, and ranges are selected with a rotary switch which connects the TE in series with one of the ranging resistors. Some commercial models also incorporate an ac-dc switch, as well a null detector, and a balancing emf source for monitoring the TE output. (The "balancing emf" referred to here and elsewhere usually consists of the voltage across a fixed resistor with current supplied by a battery and adjusted with a resistive divider or series resistors. The circuit may be quite similar to the Lindeck potentiometer shown in fig. 3, but without the milliammeter. It balances, but does not measure, the emf.) If these components are not included in the TVC, the relatively simple Lindeck potentiometer (fig. 3) can be used with a detector, which may be either a microvoltmeter or a galvanometer, to monitor the TE output.

The detector can be simply used as a null detector when an ac voltage is adjusted to be equal to a reference dc voltage (3.1), or a calibrated detector can be used to measure the changes in TVC output emf as ac and dc voltages are applied alternately. The difference between the ac voltage and the dc reference is then computed from the emf differences (3.2). Provisions are made, and instructions furnished, by some manufacturers for using either method.

3.1 A Null Method

In the "null" procedure, the ac voltage to be measured is applied to the TVC and the balancing emf is adjusted for a detector null. The two polarities of dc voltage are then applied in turn, and each one is adjusted to produce a null indication on the detector. The two voltages are measured (or read from a calibrated source), corrected, and averaged. The average is corrected for the ac-dc difference, δ, of the TVC to give the RMS amplitude of the ac voltage. For example, from eq. (4), with $\delta = -0.012\%$, $V_d+ = 200.012$ V, and $V_d- = 199.960$ V,

$$\begin{aligned} V_a &= [(200.012 + 199.960)/2] + (V_d \times -0.012/100) \\ &= 199.986 - 0.024 \\ &= 199.962 \text{ V.} \end{aligned}$$

AC voltage should be reapplied after the two dc voltage measurements, to evaluate any significant drift from the original null position. To find the magnitude of the drift, the detector can be calibrated by making a small change in the dc voltage, observing the change in detector indication, and computing the scale sensitivity in percent per division. If the drift is large, a longer warm up period should be allowed, or the "deflection method" (3.2) may be used.

In the example above, a small part of the 0.026 percent difference between the two dc voltages may be due to drift in the TVC output, but most of it is due to the dc reversal difference. These measurements are sometimes carried out with only one direction of dc voltage, and a correction equal to half the dc reversal difference is then applied. This must be done very cautiously. If the correction is applied with the wrong sign, the error is twice as large as with no correction. Of course, if the dc reversal difference is small relative to the desired accuracy, satisfactory measurements may be made using only one direction of dc current flow.

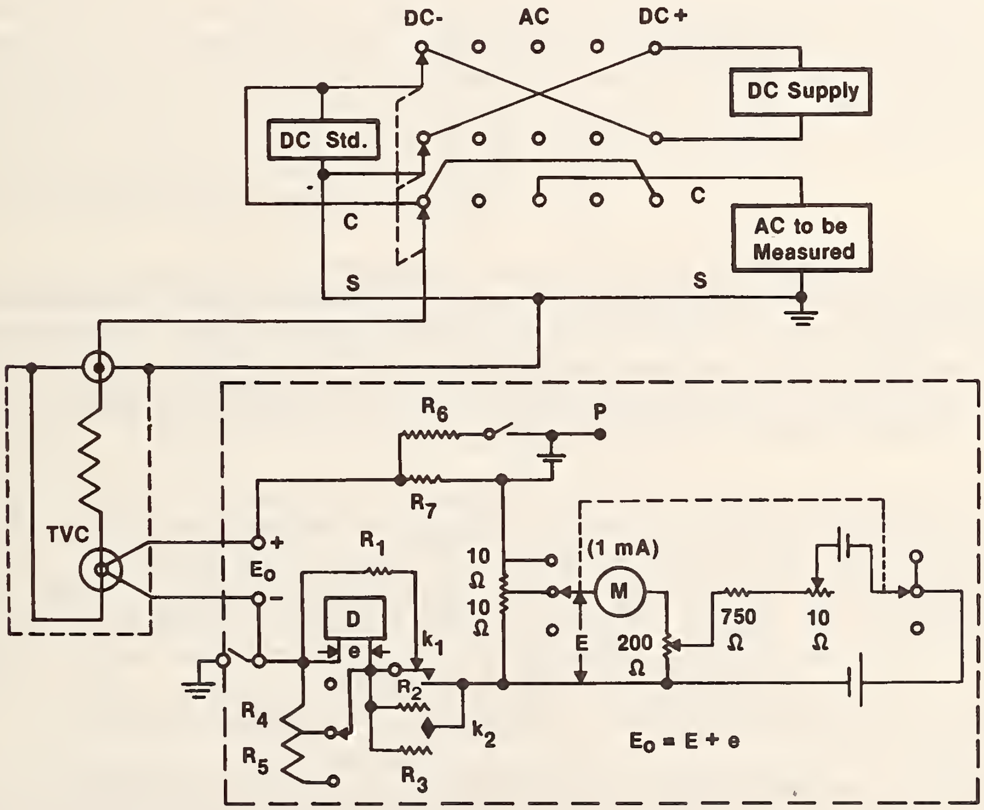

Figure 3. AC-dc switching, TVC and potentiometer for ac-dc comparisons.

NOTES:

The "DC Supply" may be a calibrator and serve as both source and standard, or the voltage may be measured with a "DC Std."--a digital voltmeter or a volt box and a potentiometer.

R_4 and R_5 (see section 3.3) and R_6 and R_7 (section 3.6) are optional. They are used to adjust and measure the detector sensitivity, respectively.

The null procedure has certain disadvantages which should be kept in mind: (A) If the dc standard is one of the widely used five or six dial calibrators, adjusting it for a detector null may be tedious and time consuming; (B) the wear on the lower two or three control switches will be accelerated; (C) the calibration of the dc standard may be in some question if a number of readings are obtained above and below the round-number value where a calibration test was made; (D) if the TVC output drift is significant during the time required for the null adjustment, it may be difficult to obtain consistent results. Where the drift rate is constant, and the measurements are made in equal time spans, the results may be consistent but in error; and (E) if the dc voltage is supplied by a power supply and measured with a volt box and potentiometer, the time required for the two adjustments (the voltage adjustment for a TVC null and then the potentiometer balance) may be even longer. The two adjustments can be made in less time if two operators work together.

3.2 A Deflection Method

A calibrated detector may be used with a TVC to measure the difference between a dc reference voltage and an ac voltage. The difference can be applied as a correction, C, to the dc voltage to obtain the value of the ac voltage.

$$V_a = V_d (1 + C) \tag{4A}$$

(see section 3.5, Calculations)

This procedure will largely avoid the problems listed above. It should also save time, as the adjustments are fewer and less tedious. The data and calculations may be a bit more complicated; however, once routine procedures are established, this method can be used with confidence. If the correctness of the results is in question, they can be verified by relatively simple extra tests, as described in section 3.5.

In the deflection method, the dc voltage is adjusted to a round-number value which is nominally equal to the ac voltage to be measured. The TVC is connected to the dc voltage (see fig. 3), and the balancing emf (or potentiometer) is adjusted for a near null on the detector. The TVC is then switched to the ac and dc voltages in the sequence indicated in fig. 3 (DC+, AC, DC-), and the small emf variations are read from the detector directly or computed from the detector readings,* as explained below. The difference between the ac and dc voltages is computed from these readings.

An equation very much like (3) in section 2.1 is used. Instead of a simple change in TVC input voltage ($\Delta V/V$), the difference between the ac voltage (V_a) and the corrected dc voltage (V_d) is measured by observing the change in TVC output. Therefore, ΔE in eqs. (2) and (3) becomes $E_a - E_d$, the emfs corresponding to the voltages V_a and V_d. The eq. (4A) above may therefore be written

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* The detector should be connected so the indication increases, or deflects up scale, when the input voltage to the TVC is increased.

$$V_a = V_d\ (1 + C) = V_d\ (1 + \frac{E_a - E_d}{nE} + \delta),$$

where, as before, n is the exponent in eq. 1, E is the output of the thermo-element, and δ is the ac-dc difference correction to the TVC.

The emfs E_a and E_d are the TVC outputs (E_o, fig. 3) with ac voltage and the two directions of dc voltage applied to the TVC. However, all but a small fraction of these emfs are balanced by the emf source or the potentiometer. The difference between the two emfs can be computed from imbalance emfs, e, read from a microvoltmeter.

The procedure is probably most straightforward when a digital microvoltmeter is used. Emfs are indicated directly in volts (μV or nV). AC and dc voltages should be applied, and emf readings taken, in time intervals which are about equal. Apply DC+, AC, and DC-, read e_1, e_2, and e_3, and compute

$$E_a - E_d = e_2 - (e_1 + e_3)/2.$$

The complete calculation is discussed in section 3.5. The digital micro-voltmeter indicates both positive and negative readings with the sign displayed, but mistakes are less likely to occur if the balancing emf is adjusted so that all readings have a positive sign.

Emfs may also be read directly from a deflecting microvoltmeter. However, it is recommended that readings be made in divisions, a deflection change, ΔD, computed, and the emf difference $E_a - E_d$ be computed from the deflection change. Techniques for reading detector scales are described in section 3.7, and multiplying factors, K, for converting ΔD to emf differences are also discussed. Calculations from data taken by this procedure are shown in table 1, column 5, where

$$E_a - E_d = (D_2 - (D_1 + D_3)/2) \times K\ .$$

Emf differences may also be measured by a calibrated galvanometer.

3.3 Electronic Galvanometers

An electronic galvanometer with appropriate sensitivity may be used to measure an emf difference, if a method is provided to determine its voltage sensitiv-ity, K, as described in section 3.6. Electronic galvanometers are available with continuously adjustable gain control over a wide range, and this feature provides a significant advantage. The sensitivity can be adjusted for maximum resolution for each measurement. On the other hand, a deflecting micro-voltmeter's sensitivity drops typically by about 60 percent if the range is increased (e.g., from 10 to 30) to keep all readings on scale.

Table 1. Examples of Calculations

In these examples, data are listed in columns 3 and 5 and identified in columns 1, 2, and 4. Test parameters are listed in the first eight lines. An emf difference, ave ΔE, is computed from emf readings e_1 to e_5 in column 3 and from deflection readings D_1 to D_5 in column 5. See text for further explanation.

1	2	3	4	5
Freq	kHz	50	Freq	50
Range	test inst.	200	Range	200
V_d	DC voltage(V)	200.006	V_d	200.006
TVC	range	200	TVC	200
E	TVC emf (mV)	8.8	E	8.8
n		1.83	n	1.83
nE		16.1	nE	16.1
μVm	range	10	μVm	10
			K	2×10^{-4}
e_1	dc	6.5	D_1	23
e_2	ac	4.4	D_2	36
e_3	dc (rev)	7.1	D_3	73
e_4	ac	4.1	D_4	35
e_5	dc	5.8	D_5	20
ΔE_1 *	μV	-2.4	ΔD_1	-12
ΔE_2 *	μV	-2.3	ΔD_2	-11
ave ΔE	mV	-0.0024	ave ΔE	-0.0024 ($\Delta D \times K$)
$\frac{100\ \Delta E}{nE}$	percent	-0.015	$\frac{100\ \Delta E}{nE}$	-0.015
δ	TVC corr %	+0.003	δ	+0.003
C	Final corr %	-0.012	C	-0.012

Notes: $^*\Delta E_1 = e_2 - (e_1 + e_3)/2$ and $\Delta E_2 = e_4 - (e_3 + e_5)/2$

e_1 and e_5 differ because of drift in the TVC output. e_1 and e_3 differ partly because of drift but mainly due to dc reversal difference in the TVC. In the statements above, substitute D for e where the readings are in divisions.

If a "one-range" instrument intended mainly as a null detector is used, an arrangement to adjust its sensitivity is often desirable. Such detectors can be shunted by resistors, such as R_4 and R_5 in fig. 3. When the potentiometer is balanced, the detector responds to currents through these resistors. The switch, which must have contacts with very low noise and thermal emfs, may select one or several shunting resistors. The resistor values should be chosen experimentally, depending on the basic sensitivity of the instrument and the sensitivity desired. Difference ratios of 2/1 or 3/1 between sensitivities are recommended. These instruments may be calibrated as suggested in section 3.6, and the scale reading techniques of section 3.7 are useful also.

3.4 D'Arsonval Galvanometers

D'Arsonval (permanent magnet, moving coil) galvanometers are often considered to be quaint, if not obsolete, by electronically oriented metrologists, and buying one for these measurements is not recommended. However, if an appropriate galvanometer is readily available, as is often the case, it should not be rejected out of hand. It is probably superior to most electronic instruments in two important respects--noise rejection and zero stability. Its sensitivity will probably be quite low unless a photoelectric galvanometer amplifier is used to increase its input voltage. However, some galvanometers may be sufficient for certain measurements where the voltage differences are large, or where there is less need for accuracy.

It is advisable to test a galvanometer for linearity if a deflection method is to be used by applying small equal changes to the potentiometer input and seeing that the resulting changes in indication are about equal on all portions of the scale. Some instruments may be nonlinear at the extreme ends, but satisfactory over most of the middle portion.

3.5 Calculations

Table 1 is intended to illustrate data logging and calculations and to suggest a data sheet format. Different data arrangements and line labels may be preferred by some users, but it is advisable to develop a more or less standardized data sheet for each type of measurement. The line labels in column 1 are brief to conserve space ($E_a - E_d$ is abbreviated to ΔE as in eqs. (2) and (3)), but they should be sufficient for a practical data sheet. Labels are further explained or defined in column 2.

In column 3, a correction, C, is determined for a test instrument indicating 200.000 V at 50 kHz. The measurements are made relative to a corrected dc reference voltage of 200.006 V. Two emf differences, ΔE_1 and ΔE_2, are computed from five readings of a digital microvoltmeter. The average ΔE is changed to millivolts to be in the same units as the TVC output, E, before being divided by nE. (Measurements and plots of n are discussed in section 7.0.) $\Delta E/nE$ is multiplied by 100 to obtain a percentage value, and the ac-dc difference correction to the TVC (δ) is added to determine the correction, C, to be applied to the dc voltage to obtain the ac value.

The same test is repeated in columns 4 and 5, but the data are read in divisions from a deflecting microvoltmeter. The line labels in columns 1 and 4 are very similar. Deflections D_1 to D_5 are read rather than emfs, ΔD_1 and ΔD_2 are computed, and the average is multiplied by conversion factor $K = 2 \times 10^{-4}$ (from table 2) to find the average ΔE in millivolts. The rest of the calculation is the same as in column 3. If data in ppm are preferred, the average ΔD can be multiplied by K=200 from table 2 to obtain -2400 nV. Then

$$\Delta E/nE + \delta = -2400/16.1 + 30 = -120 \text{ ppm} .$$

The correction, C, expressed in percent, can be applied to the reference voltage, V_d, in two ways, as illustrated below, to obtain the measured value of ac voltage, V_a. The calculation on the right may be preferable where a machine calculator is not used.

$V_a = V_d\,(1 + C/100)$	$V_a = V_d + (V_d/100 \times C)$
$= 200.006\,(1 + (0.01 \times -0.012))$	$= 200.006 + (2 \times -0.012)$
$= 200.006\,(.99988)$	$= 200.006 - 0.024$
$= 199.982$ V	$= 199.982$ V

where C is expressed in percent

*** If the accuracy of the procedure or the correctness of the sign is in question, it can be verified as follows: Increase the dc voltage by 0.020 percent after a measurement, and repeat the procedure and calculation. The correction, C, should be 0.020 percent more NEGATIVE than in the first measurement.

3.6 Galvanometer Calibration

An obvious method for calibrating a galvanometer scale in these test circuits is to introduce a small measured change in the TVC input, observe the resulting change in indication, and compute a multiplying factor, K, for converting changes in indication to voltage differences (e.g., percent/div or ppm/mm). This method has certain advantages. No n data are required, and the TVC output, E, need not be measured. It is also quite feasible in voltage measurements if the small voltage change can be measured with the dc standards being used. The change should be large enough for good resolution, but of course, the galvanometer must not deflect off scale.

This calibration method is, however, more tedious and time consuming than some alternate methods. It may also require additional equipment in ac-dc difference measurements (see 6.2) where no dc standards are ordinarily used.

Several calibration methods have been developed to introduce a known change in emf directly in the detector circuit. In one of these, a change in resistance (ΔR) in the balancing emf circuit produces a change in current and hence a change in emf. However, this requires a rather sophisticated circuit with practically constant resistance (except for the ΔR) at all emf levels.

A relatively uncomplicated calibration circuit, which requires its own battery, is shown in fig. 3. It consists of R_6 and R_7, an on-off switch and a 2400-mAh mercury battery. A computable emf, e, is inserted across R_7 (a one percent, 1-ohm resistor is recommended) by closing the switch. A round-number emf of 10 μV (R_6=135 kΩ) will be satisfactory in many instances; however, the calibrating emf should be commensurate with the detector sensitivity. A rotary switch with several contacts can be used to connect any one of several resistors in the R_6 position. It may be desirable to have more than one calibrating emf if the sensitivity of the detector is adjustable over a wide range.

A multiplying factor, K, (μV/div) is computed from the deflection observed when the voltage is inserted. The deflection change, ΔD, (sections 3.2, 6.2 and 8.0) resulting from differences between ac and dc voltages or currents, is multiplied by K to obtain the emf difference, $E_a - E_d$. This factor K is equivalent to K in table 1 (column 5). But in that example the detector is a microvoltmeter, and K is obtained from table 2.

Table 2. Conversion Factors K

Microvolts	Divisions	μV	K (x by) for 100-div scale		
μV range	(full scale)	(full scale)	div to millivolts	div to microvolts	div to nanovolts
30	60	60	6×10^{-4}	0.6	600
10	100	20	2×10^{-4}	0.2	200
3	60	6	6×10^{-5}	0.06	60
1	100	2	2×10^{-5}	0.02	20

The current drawn by the battery is, of course, minimal, and the mercury cell maintains a nearly constant voltage for most of its useful life. A new battery should last a year unless it is inadvertently left on for an extended period. It is advisable to check its voltage occasionally by connecting a voltmeter between the positive input connection and the test point "P" (fig. 3). The potentiometer switch may be either on or off.

3.7 Reading Deflecting Detectors

The scales on most suitable microvoltmeters and galvanometers have the zero indication at the center, so that positive and negative readings can be made to the right and left. Microvoltmeters with intermediate ranges--3, 30, 300, etc.--usually have scales with 30 divisions to either side of zero as well as 50-division scales for the decade ranges. This arrangement is convenient for most measurements and for null detectors. However, it is very desirable to have the zero at the far left for the procedures described here. Typical microvoltmeter scales are shown in fig. 4, but with a number plate in front of the 50-division scale. The substitute numbers are engraved on a plastic plate and filled with black wax. A similar plate can be made by cementing cut-out numbers on a transparent plate. The instrument is read with zero at the left and a full scale range of 100 divisions. It can be read in microvolts; however, some conversion to other units will probably be advantageous in the

calculations. It is probably more straightforward, and mistakes are less likely, if readings are recorded in divisions. A deflection difference, ΔD, can be computed in divisions and then converted to an emf difference, ΔE, using the appropriate factor, K, from table 2 below.

Figure 4. Typical microvoltmeter scales with three deflections marked.

Three readings are marked on the scale in fig. 4 at 23, 36, and 73 divisions as an illustration. If the reading at 36 divisions corresponds to an ac voltage or current and the others to direct and reversed-dc, then

$$\Delta D = D_2 - (D_1 + D_3)/2 = 36 - (23 + 73)/2 = -12 \text{ div.}$$

Of course, the same result is obtained when the regular scale is read, but the sign must then be observed very carefully. The readings are -27, -14, and +23, and

$$\Delta D = -14 - (-27 + 23)/2 = -12 \text{ div.}$$

Obviously, mistakes are less likely with the substitute numbers, where all readings are positive.

The scales shown in fig. 4 are typical of several instruments in which the zero and full scale indications on either scale coincide. It is feasible--and advantageous--to read the 100-division scale with any range on most of these instruments. The same substitute numbers can be used with any range, and the reading precision is better with 100 divisions. The feasibility of this procedure must, of course, be verified for any particular instrument. In the example in fig. 4, the indications marked on the 100-division scale are extended to the 60-division scale and read as 14.0, 21.5, and 43.5. Then ΔD = 21.5 - (14 + 43.5)/2 = -7.25 div. The emf difference is -7.25 μV on the 30-μV range (60 div full scale). If the corresponding reading of -12 divisions on the 100-division scale is multiplied by 0.6 from table 2, essentially the same result is obtained.

The table gives factors, K, for converting deflection changes to mV, μV, and nV for the four most-used ranges. As indicated in the text, a conversion to mV is preferred for results in percent while nV are more convenient for ppm.

3.8 Peak and Average Responding Instruments

Peak and average responding instruments are widely used for certain applications, and their principles can be adapted for ac-dc comparisons. They are not electrothermic and are therefore outside the intended scope of this writing. However, since at least one peak comparator [11], a peak calibration method [12], and one average responding ac-dc comparator [13] have been developed, they are noted here and referenced. The accuracy of these comparators is sufficient for many applications; however, they are more limited in voltage and frequency range than electrothermic instruments. These comparators are not commercially available at this time.

4.0 Switches and Potentiometers

As noted earlier (3.0), some commercially available multirange TVCs have provisions for ac-dc switching as well as an adjustable emf source and a detector for monitoring the thermoelement output. If these components are not included, or if single-range TVCs, thermoelements or TCCs are to be monitored, the equipment described in this section is not difficult to build, and the parts are readily available. The circuits are shown in some detail in fig. 3, and of course, variations can be made to meet particular needs. The diagram of the potentiometer includes two optional features, as noted below the caption, which were discussed in previous sections.

4.1 AC-DC Switches

The ac-dc switch shown in fig. 3 connects the TVC to either direction of dc voltage, or to the ac voltage to be measured, in the order suggested in section 3.2. Other switch arrangements, such as reversing dc with a separate switch, should be satisfactory also. The ac input to the switch, and the cable connection to the TVC, should be coaxial to minimize electromagnetic interference and circuit impedance. The switch and the potentiometer should be in separate shielded enclosures, and the cable to the detector, D, input should also be shielded.

The dc voltage may be supplied by a calibrator which serves as both source and standard, or a separate standard (a volt box and potentiometer or a digital voltmeter) may be connected at the terminals for "DC Std." The standard should not be appreciably affected by changing the polarity of the applied voltages. At very low voltages, where the voltage drop across the line resistance may be significant, the dc voltage should be monitored at the "DC Std." terminals. The cables with conductors c and shields s (fig. 3) should have equal resistance (identical cables are preferable) to equalize the voltage difference between the ac and dc voltage terminals and the comparison points at the switch contacts.

The ac-dc circuit should have only one ground point, usually, but not necessarily, at the ac source. The switching circuit shown in fig. 3 provides

a direct connection from the TE to ground. It is preferable to have no switch in this part of the circuit. If a switch is used, and if it opens an instant before the switch contact in the input side, the insulation between the thermoelement heater and the thermocouple will probably be punctured by an excessive voltage.

4.2 Lindeck Potentiometers

A two-range (10- and 20-mV) potentiometer is shown in fig. 3. It is powered by a 1.35-V mercury battery and controlled by two helical resistors, which may be either the 3- or 10-turn devices currently available. If the "deflection method" proposed in section 3.2 is used, the fine (10-ohm) control need not have resolution sufficient for an exact null. The controls are adjusted for a detector indication in the portion of the scale where the first reading (e_1, section 3.2) should be made.

If the 1-mA meter (M) is omitted, the instrument is a balancing emf source which cannot measure the TE output. However, as noted earlier (3.2), the emf can be measured by the detector if the detector is a microvoltmeter. Select a range to measure 10 mV or more, turn the balancing emf off, and close the key (k_1).

As noted in the caption (fig. 3), the resistors R_4 and R_5 (section 3.3) and R_6 and R_7 (section 3.6), and their associated switches, are used to adjust and measure the sensitivity of the detector, D. These components may be omitted if the detector is a microvoltmeter, or if a null method (3.1) is used.

The potentiometer and detector should be grounded, preferably at the negative input to the detector. This is sometimes done by linking the detector input to ground through the detector's power cord. A few instruments may have the negative output connected to the instrument casing which is grounded. However, it is preferable to connect the circuits to the grounded potentiometer shield by closing the switch at the negative input terminal (fig. 3), or by some other link at this point.

4.3 Detector Keys

The detector keys k_1 and k_2, and the three associated resistors (fig. 3), are typical of those used in these procedures. Key k_1 should have low-thermal contacts and low contact resistance. A two-position lever switch is recommended for k_2. The contacts should be good, but a quality less than that of k_1 should be satisfactory. The resistor R_1 is always in parallel with the detector, unless k_1 is closed for a detector reading. This keeps the detector "quieter" when the key is open. R_1 also serves to reduce the detector sensitivity when k_2 is closed for preliminary balance adjustments. It should not be necessary to switch a multirange detector to a higher range for preliminary balances with this key configuration. An R_1 of 100 ohms is satisfactory for most high-impedance detectors. R_2 and R_3 should be chosen experimentally, depending on the range most often used and individual preference. However, 20 kΩ and 100 kΩ, respectively, may be useful as values to start with.

5.0 AC-DC Difference

The ac-dc difference in a thermal voltage converter is nearly all due to reactance in the ranging resistors, the range selector switch, and other switches and connections in the ac-dc circuit. Series inductance will impede the ac current, so that more ac than dc voltage is required for equal TE current--and thermocouple output. The sign of the correction is, by eq. (4), positive in this case. A positive correction can also result from ac current being lost to ground by capacitance. However, capacitance between resistors connected in series, or between turns of wire in a wire-wound resistor, will increase the TE current for a given ac voltage and result in a negative correction. Compensation for this effect is sometimes provided by adding capacitors to ground which bypass the TE and part of the series resistors.

5.1 AC-DC Difference Corrections

AC-dc difference corrections can be plotted conveniently on a semilog scale as in fig. 5, and such a plot can be used to find good estimates of corrections at frequencies where determinations were not made. Fig. 5 illustrates a typical set of correction curves where the specified error limits are +a to -a. Low-voltage ranges in a multirange TVC usually have small corrections (curves A, B, and C). Intermediate and high-voltage ranges are often limited to lower frequencies (curves D and E), because the effects of reactive components are larger and more difficult to control. The useful frequency range at high voltage is often extended by adding compensating elements as mentioned above. Optimum compensation (curve F) will sometimes result in a change in direction (and sign) of the correction, and the change in magnitude is usually rapid after the sign change.

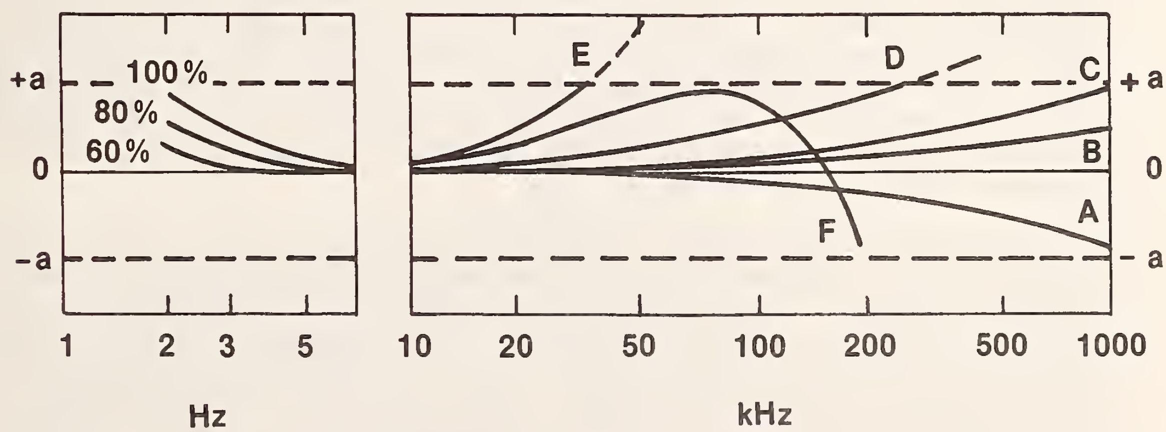

Figure 5. AC-dc difference correction curves.

It is usually sufficient to make only one determination of ac-dc difference at low and intermediate-voltage ranges. This determination should be at the highest frequency of interest. If the instrument is used only at audio frequencies, a test at 20 kHz is often sufficient, even on high-voltage ranges. The correction curve can be expected to approach zero rapidly, and if the instrument is designed for use at 50 to 100 kHz, the correction should be quite negligible at 10 kHz and lower. Where corrections are relatively large, or if there is evidence of a curve such as F (fig. 5), additional determinations should be made.

5.2 AC-DC Difference in Thermoelements

The low-range thermoelements used in TVCs (2.5 to 10 mA) rarely add significantly to the ac-dc difference of the instrument. The TE response to ac current is affected by two or three thermoelectric phenomena which, incidentally, are quite independent of frequency. However, the result of these effects is less than 5 ppm for most low-current TEs. It should not be necessary to redetermine the ac-dc difference of a TVC after a TE is replaced, and new TEs furnished by the instrument manufacturer should not require ac-dc difference tests before being installed. However, if they are tested, they should be treated as current converters (i.e., tested in series with a standard TE), as they respond to the current through the series resistors. The TE acts more as a voltage converter on very low ranges where its impedance is a large part of the total.

AC-dc difference in higher-range vacuum TEs is larger due to skin effect in the current conductors leading to the heater. The copper-coated nickel alloy widely used to pass current conductors through glass seals is sufficiently magnetic to cause a small increase in impedance. Therefore, more heating is produced with ac current than with equal dc current. AC-dc difference resulting from skin effect usually varies from about 0.005 percent at 200 mA to between 0.01 and 0.02 percent at 1 ampere--the highest range now available in vacuum bulbs. The effect in the low-current TEs used in TVCs is nearly always negligible. However, it may account for very small positive corrections in some 0.5- and 1-volt ranges, and in the low-voltage TVCs (0.3 to 1 volt) used with ac shunts for current measurements. The shunt and TVC combination is ordinarily tested and used as a unit. However, the ac-dc difference of the TVC can be determined and appropriate corrections applied (see section 8.0 and reference [16]).

TEs for currents of 10 amperes and higher sometimes have a tubular heater, or a heater with a C-shaped cross section made from a flat material. The heater is mounted between heavy copper support blocks with terminals at either end. The ac-dc difference of these elements can be very much dependent on the location of other conductors, particularly the return conductor, which is usually placed close to, and more or less parallel to, the TE heater. AC current will distribute itself for minimum reactance, and may therefore be concentrated close to, or away from, the thermocouple which is attached to the side or top of the heater. This nonuniform current distribution can cause ac-dc differences as large as 0.03 percent. The ac-dc difference of these TEs can be made constant by mounting both terminals on one end of the

device and connecting a rigid copper conductor between one terminal and the heater support at the other end. This conductor can also be placed, relative to the heater, for minimum ac-dc difference.

Practically all low-frequency (below 60 Hz) ac-dc differences in thermoelectric transfer instruments are due to the thermoelement [9]. At most frequencies the heater temperature, and therefore the TE output, are essentially constant. However, at low frequencies the heater is cooled slightly between peaks of ac current by conduction through the heater supports and the thermocouple wires. This effect is greater in high-current TEs and may be detected up to about 60 Hz on some ampere-range TEs. However, in 2.5- to 10-mA TEs used in TVCs the effect usually occurs below 5 or 10 Hz. It also decreases sharply as the heater current is reduced on all current ranges. Correction curves for three current levels in one TE are illustrated in the left-hand portion of fig. 5.

6.0 AC-DC Difference Measurements

AC-dc difference corrections to a transfer instrument (TVC or TCC) under test, δ_t, are determined relative to a similar standard whose corrections, δ_s, are known. Corrections to a standard or reference TVC or TCC are determined at the National Bureau of Standards and other laboratories. Measurements of $\delta_t-\delta_s$ may be made by either of the two methods outlined below. Fig. 6 shows a typical test arrangement for comparing two TVCs. AC and the two directions of dc voltage are connected to the TVCs successively by the ac-dc switch. Note that both TEs are connected directly to ground as in fig. 3. The switch shown in fig. 3 can also be used in ac-dc difference measurements. However, the switching sequence indicated in fig. 6 may be preferable, and the switch is a bit simpler. The TVC outputs are monitored with detectors (D) after being balanced by the emf sources (B), each of which may be a potentiometer, as in fig. 3.

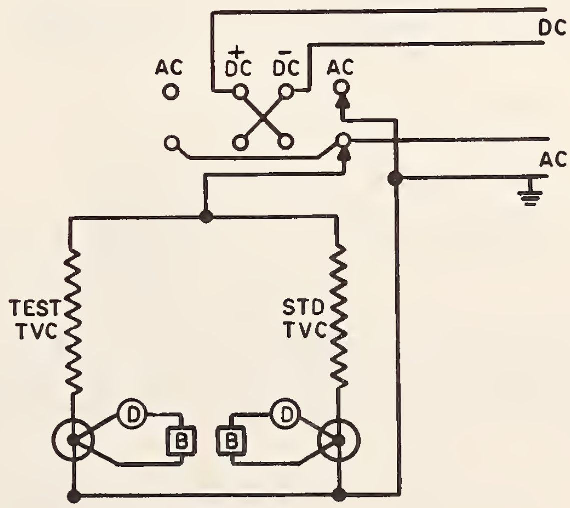

Figure 6. Circuit for ac-dc difference measurements.

The power supplies need not be calibrated; however, if the "null method" is used, provisions must be made to measure the dc voltage. The dc supply must have fine controls, with resolution of a few ppm, for adjusting the input to the test TVC for equal output on both directions of dc voltage. AC voltage may be supplied by an oscillator, amplifier, and appropriate transformers. Fine control for the ac voltage is necessary if the deflection method is used. Control circuits are discussed in section 6.4.

6.1 A Null Method

AC-dc difference can be measured using a procedure in which only null readings are made on the detectors used with the TVCs. This method is similar to the "null method" described in section 3.1 for voltage measurements. In this procedure, ac voltage is applied first, and both balancing emfs are adjusted to null the detectors. DC voltage is then applied, adjusted for a null on the test TVC detector, and measured (or read from a dc calibrator). The dc voltage is then readjusted for a null on the standard TVC detector and measured. In the example below, these voltages are listed on the line labeled "DC+." DC voltage of the opposite polarity is then applied, adjusted for the two nulls, and measured as before. ("DC-" in the example.) The ac voltage should then be reapplied, and any drift from the original null position on either detector should be evaluated for significance. If either TVC output is drifting appreciably, more warm-up time should be allowed, or the deflection method (6.2) may be used.

The relative ac-dc difference between the two TVCs in volts is equal to the difference between the average of the dc voltages required for nulls on the standard TVC and those required for nulls on the test TVC. The difference is usually converted to percent (or ppm) as in the following example.

Voltage	Voltages required for detector nulls	
	Test TVC (V_t)	Std. TVC (V_s)
DC+	200.000	199.952
DC-	200.032	200.010
Ave DC	200.016	199.981

$\Delta V = V_s - V_t$	-0.035 V
Relative ac-dc difference	-0.018%
δ_s(Std.) known	+0.003%
δ_t(Test)	-0.015%
or	-150 ppm

This procedure requires no galvanometer calibration or measurements of n. However, the adjustments are tedious and time consuming, dc standards are necessary, and the disadvantages discussed earlier (3.1) are present here also.

6.2 A Deflection Method

The deflection method for making ac-dc difference measurements is similar to the one described in section 3.2 for making ac-dc voltage comparisons. DC

voltage is applied to both TVCs, and the balancing emfs are adjusted to null both detectors. AC and the two directions of dc voltage are adjusted in turn to obtain a null indication on the detector used with the test TVC. The corresponding indications on the standard TVC's detector are recorded, and an emf difference, $E_a - E_d$, is computed as in section 3.2. The ac-dc difference of the test TVC, δ_t, (defined in section 2.4) is determined by evaluating $E_a - E_d/nE$ and applying a correction for the ac-dc difference of the standard TVC, δ_s.

$$\frac{V_a - V_d}{V_d} = \frac{E_a - E_d}{nE} + \delta_s = \delta_t$$

In this application, V_a and V_d are the ac and dc voltages required for equal response from the test TVC. The emf difference, $E_a - E_d$, can be computed from readings taken from a digital microvoltmeter or a deflecting detector, as discussed in section 3.2, and the scale reading techniques described in section 3.7 are useful here also. The reading sequence suggested for voltage measurements (DC+,AC,DC-) may be used for ac-dc difference measurements. However, it is probably advantageous to take four readings in the sequence suggested in fig. 6 (AC,DC+,DC-,AC). Either sequence will minimize the effects of drift in the TVC outputs, if the readings are taken at time intervals that are about equal. The second reading with ac voltage should increase the reproducibility.

A measurement made with a deflecting detector can be illustrated using the indications from fig. 4. If it is assumed that there is no appreciable drift, so that both readings on ac voltage are equal (i.e., 36 divisions), then

$$\Delta D = (D_2 - D_1 - D_3 + D_2)/2 = (36-23-73+36)/2 = -12 \text{ div.}$$

If $nE = 16.1$ mV, $\delta_s = +0.003\%$ and $K = 2 \times 10^{-4}$ mv/div (10 μV range--table 2), then

$$\delta_t = -0.015 + 0.003 = -0.012\%.$$

6.3 TE Comparators

Stable power supplies are necessary for accurate measurements, and instability is probably the major cause of nonreproducibility in ac-dc difference comparisons. This difficulty can be largely overcome by using a TE (thermoelement) comparator. The instrument is not commercially available at this time; however, it is not difficult to build. A brief description of the general principle and advantages is given below. A more complete discussion is left to the referenced papers. TE comparators have been built in at least three configurations [9,10,14], but they all employ a divider circuit to which the emfs from the test and standard TVCs are connected. The divider is adjusted, nulling a detector, and at this point the divider setting corresponds to the ratio of the emfs.

The comparator sketched in fig. 7 shows a typical circuit. The potentiometer (Pot'r) is used, with key k_1, to measure both emfs and to monitor the test TVC output. The divider (DIV) is a two-dial Kelvin-Varley, the second dial being a ten-turn helical resistor. The lower emf, which may be either from the test or standard TVC, is balanced against a portion of the higher emf by adjusting the divider. A balance is indicated by a null reading on the microvoltmeter (μVm) with key k_2 closed. After this preliminary balance, the ac and dc voltages are applied in the sequence indicated, and each voltage is adjusted to give a test TVC output equal to the Pot'r emf. Then with key k_1 open, k_2 is closed and an emf is read from the μVm. These emfs differ because of ac-dc difference and dc reversal difference. If both directions of dc voltage are used, the ac-dc difference can be computed from them.

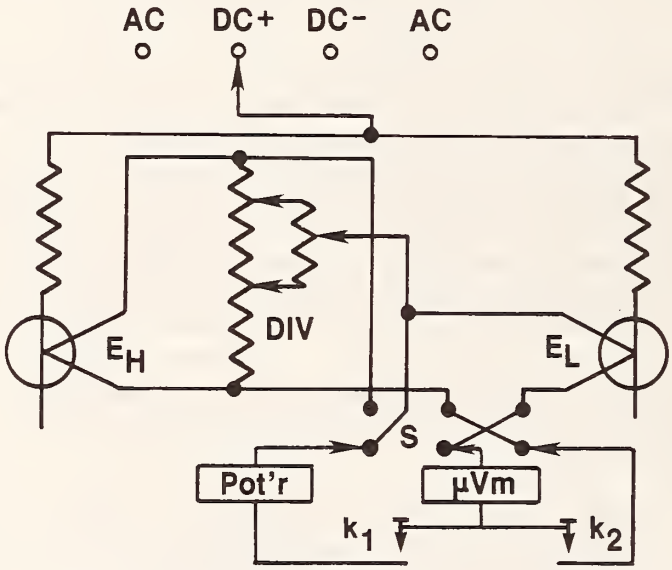

Figure 7. TE comparator with two TVCs and ac-dc switch.

Small fluctuations in the power supply output will produce nearly equal proportional changes in the emfs, and the divider balance will not be affected appreciably. The stabilizing effect is greater if the TEs have well-matched time constants and response characteristics (n values), but even if they are not quite matched, the effect usually affords a significant advantage. A second advantage is that the ac and dc voltages do not have to be adjusted for equal output from the test TVC so exactly as in other test methods. Actually, if the test and standard TEs were quite similar, and the dc reversal differences were small, it should not be necessary to adjust or monitor the test TVC output at all, once the ac and dc voltages are adjusted to be nearly equal. However, TEs usually differ enough to make adjustments to near equal output necessary for accurate measurements of ac-dc difference.

An automated model of this comparator is described in reference [15].

6.4 Voltage Control Circuits

Measurements of ac-dc difference require very fine voltage adjustments to produce equal output from the test TVC. Fine controls are required for dc

voltage in the null method, and for both ac and dc in the deflection method. AC and dc voltages are often supplied by five- and six-dial calibrators. The lower two or three dials can be adjusted for a detector null; however, this method is not very satisfactory. The knobs are often small, close together and not easily turned. An exact null may not be obtainable with the resolution available, and it is sometimes difficult to place the supply within easy reach of the operator.

The series resistance control shown in fig. 8 is recommended as a substitute fine control for voltages from 1 to 1000 V. It is placed between the dc supply and the ac-dc switch for dc voltage control, or between this switch and the TVCs to control both ac and dc voltage. The voltages are set to be nearly equal with the regular controls, and the final fine adjustments are made with this control. It can be built into a shielded box and connected into the line by a two-conductor shielded cable. It can then be placed where most convenient for the operator. It is important to remember that the control carries the test voltage which is often high enough to be dangerous. The casing must therefore be well insulated, and the shield firmly grounded. This control can, of course, be used with other power supplies which do not have sufficient fine controls. The voltage across the control, and hence the voltage at the TVC terminal, is adjusted with the ten-turn, 1-kΩ, helical resistor R_1. The sensitivity is adjusted by shunting R_1 with any one of 10 resistance values R_2. The value of R_2 is selected by a rotary switch, and is increased as the voltage increases. A resistor R_3 of about 250 ohms prevents R_2 from being shorted and improves the linearity. The most appropriate setting for R_2 depends not only on the voltage level and user preference, but on the current drawn by the TVCs--usually 5 to 20 mA. The recommended value of resistance for each switch setting is listed in table 3 below. Each successive step increases R_2 by 50 to 70 percent.

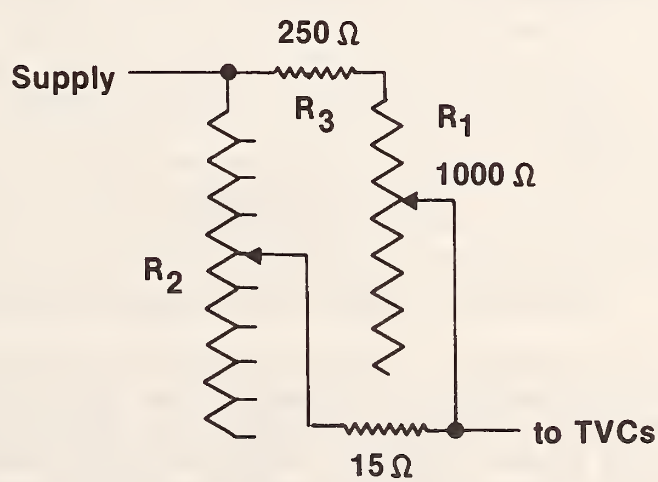

Figure 8. Series resistance fine control for ac and dc voltages.

Table 3. (see fig. 8)

Switch position	Resistance of R_2 (ohms)	Switch position	Resistance of R_2 (ohms)
1	15	6	150
2	25	7	250
3	40	8	400
4	60	9	650
5	100	10	1000

* * * * *

AC voltage and current from an oscillator-amplifier supply can be controlled with the circuit shown in fig. 9, which regulates the input signal to the amplifier. Resistor R_1 is a ten-turn helical resistor for coarse control, and adjusts the amplifier input from zero to near the oscillator output voltage. The control is less coarse if this resistor is operated near full range. The oscillator gain should therefore be set for an amplifier output only slightly higher than that necessary for the desired output voltage. An R_1 of 1 kΩ is suitable for most oscillators, but 10 kΩ may be necessary for those with relatively high output impedance.

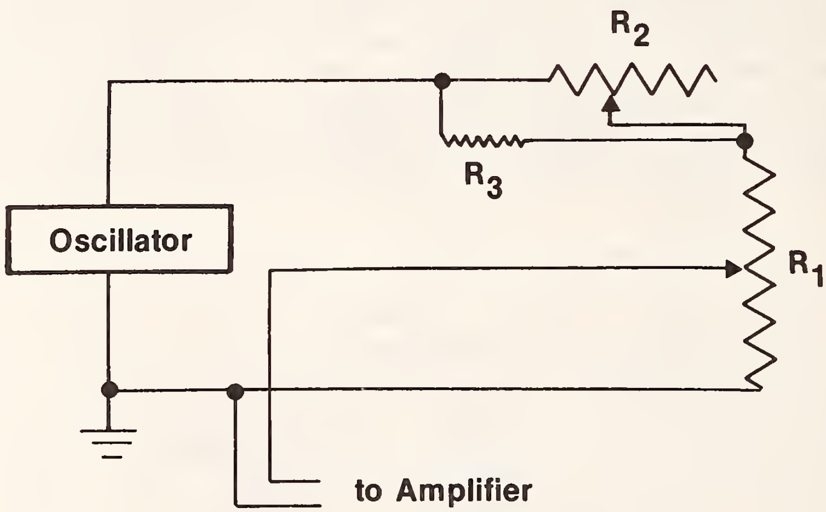

Figure 9. Control for an amplifier input.

Fine control is provided by a ten-turn helical resistor R_2 of 100 ohms and a shunt R_3 which regulates the sensitivity. The value of R_3 depends on several factors in addition to personal preference, but 20 to 50 ohms is usually satisfactory. The control assembly should be well shielded. If it is connected to the oscillator and amplifier through a shielded three-conductor cable, it can be moved around and placed conveniently for the operator.

6.5 Verifying AC-DC Difference Corrections

AC-dc difference corrections are primarily due to reactance in the switches and resistors in the TE circuit (see section 5.0). They are not likely to change, if these components are rigidly mounted and spaced so that capacitance between components, and between components and ground, is not excessive. Changes are probably more likely, if fixed and adjustable capacitors are added for frequency compensation. This is often done in multirange TVCs for the higher voltage ranges. If repairs or alterations are made that might affect these circuits, the ac-dc difference corrections should be redetermined.

If there is no reason to suspect that a change has occurred, then recalibration at NBS or other laboratories can be several years apart. (Five-year intervals are reasonable.) However, it is advisable to make periodic comparisons between TVCs within a laboratory to detect any changes that might have occurred. Such tests are especially valuable at high voltages and frequencies where changes are most likely.

Tests are made most easily between adjacent ranges in a set of single-range TVCs, or between members of two sets. If these tests are made accurately, it should not be necessary to send the entire set to another laboratory for recalibration. A few ranges, perhaps a low, medium, and high range, would serve as a basis for determining corrections to the other ranges by intercomparison. Of course, other sets and multirange instruments can be compared with such a set.

If two multirange TVCs are available, one can be calibrated relative to the other. Such periodic comparisons will assure that no changes have occurred as long as the results are the same from one test to the next. It is very unlikely that both instruments will change equally and simultaneously.

If only one multirange TVC is available, no intercomparisons can be made. However, the procedure outlined below should be useful in detecting any significant changes in the ac-dc difference corrections. It consists of measuring the difference between a constant ac voltage and the average of the two polarities of a constant dc voltage at rated voltage on a given range and then immediately with the same voltages on the next higher range (e.g., 50 volts on the 50-volt and the 100-volt ranges). If the voltages are stable during the test, the difference between the ac-dc difference corrections of the two ranges ($\delta_1 - \delta_2$) can be computed. The voltage difference can be determined by evaluating $(E_a - E_d)/nE$ as in section 3.2, and from the equation in section 6.2,

$$\frac{V_a - V_d}{V_d} = \frac{E_a - E_d}{nE} + \delta.$$

Then, since $(V_a - V_d)/V_d$ is the same,

$$\delta_1 - \delta_2 = \frac{E_{a2} - E_{d2}}{n_2 E_2} - \frac{E_{a1} - E_{d1}}{n_1 E_1},$$

where the subscripts 1 and 2 refer to the two ranges.

This procedure is more likely to be used on instruments with built-in detectors and balancing emf circuits, so that E and n values may not be known. However, the detector can be calibrated directly by making a small change in the dc voltage, observing the resulting deflection change, and computing a multiplying factor, K, (ppm/div) as suggested in section 3.6, first paragraph.

In the example of actual data below, multiplying factors K_1 and K_2 were determined for the 50- and 100-volt ranges of a typical multirange TVC. The sensitivity of the 100-volt range was, of course, low (38 ppm/div) as only 50 percent of rated voltage was applied. AC voltage at 100 kHz and the two polarities of dc voltage were then applied in the sequence DC+,AC,DC-,AC,DC+,AC,DC-, and seven deflections, D_1 to D_7, were observed. Then

$$D_a = D_2 - (D_1+D_3)/2, \quad D_b = D_4 - (D_3+D_5)/2, \quad D_c = D_6 - (D_5+D_7)/2 ,$$

and "ave ΔD" is the average of the three. K is in ppm/div and

$$\delta_1 - \delta_2 = (\Delta D_2 \times K_2) - (\Delta D_1 \times K_1) ,$$

where the subscripts 1 and 2 refer to the 100- and 50-volt ranges, respectively.

Range	D_1	D_2	D_3	D_4	D_5	D_6	D_7	ave ΔD	K	$\Delta D \times K$
100	23.0	14.0	25.0	14.0	23.0	13.5	25.0	-10.2	38	-390
50	27.0	12.5	23.5	12.0	25.0	12.0	22.5	-12.2	8.6	-100

The ac-dc differences of the 100- and 50-volt ranges at 100 kHz were +210 and -90 ppm, respectively, when measured by conventional methods. These corrections differ by 300 ppm, and the voltage comparisons indicate a difference (δ_1 - δ_2) of 290 ppm. This agreement is closer than in most of these tests; however, changes on the order of 50 ppm should be detected readily enough by this method.

Accurate knowledge of the ac and dc voltages is not necessary, and the need for equality is only that all readings be within the range of the readout detector. It is necessary, of course, to ensure that neither voltage changes significantly during the few minutes required for a measurement. Changes are more likely when the TVC range, and hence the load on the supplies, is changed. However, the loads are very small--usually 2.5 and 5 mA--and most ac and dc calibrators are well enough regulated to remain stable during these changes. An additional load resistor can be inserted in parallel with the TVC for a few seconds to roughly double the current drawn. No significant change in the TVC detector balance should be observed. A repeat test after a few minutes with consistent results will indicate that one voltage is not drifting relative to the other.

If stable calibrators are not available, the voltages may be monitored with digital voltmeters. However, most ac DVMs currently available are limited to 4-1/2 digits, and this resolution is marginal at best in this application.

7.0 Measurements of n

The measurements described thus far are made to determine small voltage and current differences by evaluating $(E_a - E_d)/nE$. As noted earlier (2.1), the factor n is near 2 at very low currents, but usually 1.6 to 1.9 at rated currents. The expression above can be evaluated if n is predetermined in a special test using dc voltage or current. Values of n corresponding to any value of E can be found, if a curve is plotted of n versus E. Four or five determinations between 50 and 110 percent of rated heater current are sufficient.

From eqs. (2) and (3),

$$n = \frac{\Delta E}{E\ (\Delta I/I)}, \text{ and for a TVC, } n = \frac{\Delta E}{E\ (\Delta V/V)}$$

Measurements of n are made by introducing small measured proportional changes in TE heater current ($\Delta I/I$) and measuring the resulting output, E, and changes in output, ΔE. Current changes should be large enough for good resolution, but small enough to keep all detector readings on scale. Changes of a few tenths to about one percent are usually convenient.

These tests are probably made more conveniently on the 100-V range of a multirange TVC, and n values obtained on one range can be used with any range, if they are correctly related to the TE output. Low-voltage, single-range TVCs can be placed in series with additional resistance, and more manageable voltages can then be applied. Low-range TEs (2.5 to 10 mA) may be connected in series with 50 to 200 kΩ and appropriate voltage applied for the desired heater currents. The voltages may be supplied, and small voltage changes "dialed in," from a dc calibrator. Or the voltage may be supplied by a stable dc power supply with fine controls, and small changes measured with a digital voltmeter or a volt box and potentiometer.

In the example below, one determination of n is made by applying 90.000 and 90.500 volts for a proportional change of 0.00556, and E = 8.51 mV. Imbalance emfs, e, are read from a digital microvoltmeter, and three emf changes are computed from seven readings.

$$\Delta E_1 = e_2 - (e_1 + e_3)/2, \quad \Delta E_2 = e_4 - (e_3 + e_5)/2, \quad \Delta E_3 = e_6 - (e_5 + e_7)/2$$

Successive readings are made at the alternate voltages--90.0 and 90.5. The average of the three emf changes (80.4 µV) is converted to 0.0804 mV for the calculations.

V	ΔV	E	e_1	e_2	e_3	e_4	e_5	e_6	e_7	ave ΔE	ΔV/V	n
90	0.5	8.51	12.3	92.8	11.4	91.2	10.8	90.8	10.4	0.0804	0.00556	1.70

Current changes can also be introduced in a TVC, or in a TE in series with a high resistance, by inserting a known resistance change in the TE circuit. A relatively low resistance, with a switch for shorting it, is placed in series with a TVC or TE, and as the switch is opened and closed, $\Delta I/I = -\Delta R/R$. The power supply must, of course, be well regulated, and the resistance ratio $\Delta R/R$

should be known to about one percent. The calculations are simplified, as $\Delta I/I$ is the same at all voltage levels. The change can, of course, be a round number. A 400-Ω resistor in series with a 40-kΩ ,5-mA, 200-V TVC will introduce a change of 0.01 (one percent) at all voltage levels.

Currents higher than 10 mA are usually measured with a potentiometer and a shunt in series with the TE.

The TE output emf, E, can be measured with a Lindeck potentiometer (fig. 3), or it can be measured by the detector, if a microvoltmeter with a 10-μV range is used, by turning the potentiometer off and closing key k_1. Emf changes, ΔE, are measured by the detector as described in section 3.2.

It is difficult to measure n with an accuracy better than about one percent. However, that accuracy is sufficient, as errors in n have a second-order effect on the end result. A one percent error will result in an equal error in measuring a difference, say of 0.05 percent, between an ac voltage and a dc reference voltage. However, this will affect the ac voltage measurement by only 0.0005 percent (5 ppm).

8.0 Current Measurements

Thermoelements are sometimes used as thermal current converters (TCCs), and they are usually excellent up to about 100 mA. They have ac-dc differences at higher currents, as discussed in section 5.2, which can be evaluated, and corrections can be applied. However, TCCs usually consist of a set of special ac shunts and a low-voltage (0.3 to 1 volt) TVC. In some commercial models, the shunt output is connected to the TE in a multirange TVC through a special connector. These TVCs include a balancing emf source and a detector for monitoring the output of the TE. Instructions for using these instruments are, of course, furnished by the manufacturers.

Shunts can also be connected to a low-voltage, single-range TVC, and its output can be monitored with an emf source or a potentiometer like the one shown in fig. 3. The detector may be any one of the four instruments discussed in 3.2, 3.3, and 3.4. Techniques for galvanometer calibration (3.6) and detector readings (3.7) are also useful with TCCs.

AC current may be measured, and ammeters calibrated, with the equipment and circuit shown in fig. 10. The procedure is very much like the deflection method described in section 3.2 for voltage measurements. DC current is adjusted to be nominally equal to the ac current, and the balancing emf or potentiometer (P) is adjusted for a near null indication on the detector (D). The indication, e_1, of the detector is recorded. The TCC is then switched to ac current, the ac supply is adjusted for the desired indication on the instrument under test (Test AM--fig. 10), and the detector indication, e_2, is recorded. Reversed-dc current is then applied to the TCC, adjusted to the nominal value, and e_3 is recorded. The difference between the ac and dc currents is then computed from the equation,

$$\frac{I_a - I_d}{I_d} = \frac{E_a - E_d}{nE} + \delta_s ,$$

where δ_s is the ac-dc difference correction to the TCC, and

$$E_a - E_d = e_2 - (e_1 + e_3)/2.$$

If the detector is a deflection instrument,

$$E_a - E_d = (D_2 - (D_1 + D_3)/2) \times K.$$

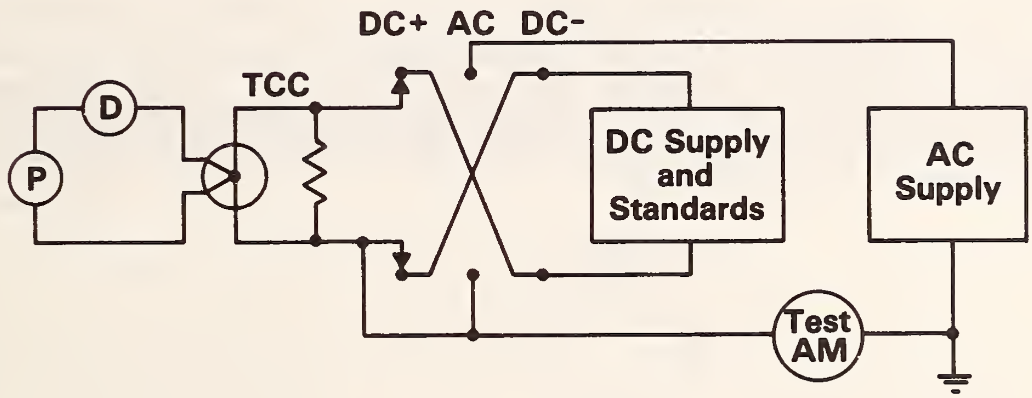

Figure 10. Circuit for current measurements using a thermal current converter (TCC).

The calculations illustrated in 3.5 are then practically the same as those for current measurements. I is substituted for V, and TCC for TVC, in table 1.

The ac-dc difference of a TCC can be determined, relative to a standard instrument, with the circuit shown in fig. 11. The equipment and switch may be the same as those in fig. 10, but no dc standards are required. The switching sequence may be as shown (DC+, AC, DC-), although the sequence suggested in 6.2 (AC, DC+, DC-, AC) may yield greater reproducibility. The switch shown in fig. 6 may be used if the current-carrying capacity is sufficient.

Each TCC output is monitored with a balancing emf, or potentiometer (P), and detector (D). A method similar to that suggested in 6.2 may be used. The ac and dc currents are adjusted for equal response (output emf) from the test TCC, and imbalance emfs are read from the detector used with the standard TCC. If four readings are taken, e_1 and e_4 are read with ac current, and e_2 and e_3 with the two directions of dc current. Then

$$E_a - E_d = (e_1 - e_2 - e_3 + e_4)/2,$$

or

$$E_a - E_d = ((D_1 - D_2 - D_3 + D_4)/2) \times K,$$

and

$$\frac{I_a - I_d}{I_d} = \frac{E_a - E_d}{nE} + \delta_s = \delta_t$$

where δ_t and δ_s are the ac-dc difference corrections to the test and standard TCCs.

If the shunts have shields or casings (dashed lines in fig. 11), it is recommended that they be connected as shown in fig. 11. If one shield were attached between the shunts, a small capacitive current might flow between that shield and ground. This current would flow through one shunt, but not the other, causing an error.

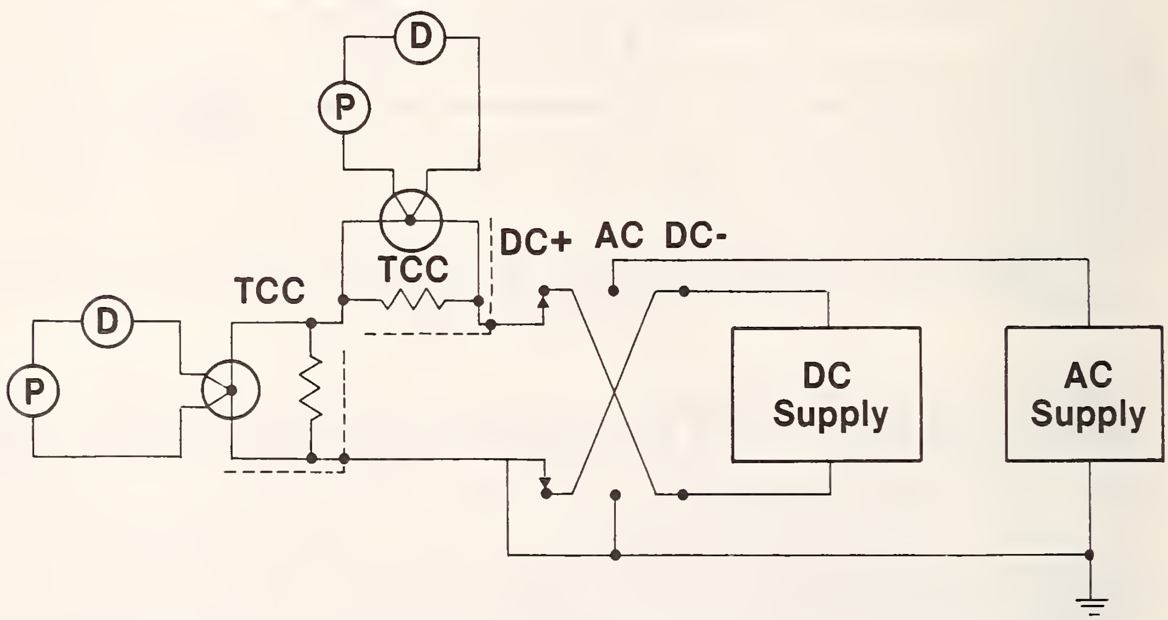

Figure 11. Circuit for ac-dc difference tests of thermal current converters (TCC).

Additional suggestions for building and using TCCs are found in reference [16] where the following are discussed:

(A) Members of a set of shunts can be intercompared very much as TVCs are (see sections 6.0 to 6.5), and corrections determined for each shunt and TE combination relative to two or three ranges which have known corrections.

(B) A "short set" of shunts can be built in which each shunt in the set is used with two TVCs (0.3 and 0.6 V) to form two current ranges. Thus the two

TVCs and six shunts provide 14 ranges. It is, of course, necessary in this arrangement that the TVC correction be negligible or that a correction, δ_T, be applied. AC-dc difference in low-voltage TVCs is mainly due to skin effect in the input leads to the thermoelement heater (5.2). This effect can be practically eliminated by using TEs with platinum lead-in wires. Such elements are available from one or two manufacturers upon special request, and at a reasonable price.

(C) If the TVC corrections are appreciable, they can be determined relative to other TVCs with known corrections. Then, at high and middle ranges, the ac-dc difference of the shunt and TVC combination, δ_C, is practically equal to the sum of the ac-dc differences due to the admittance of the shunt, δ_S, and the impedance of the TVC, δ_T. As discussed in the referenced paper, this separation of correction components is not feasible at low currents (less than 0.25 A in most cases) where the TVC carries a substantial portion of the total current. These low-range TCCs should be tested and used as shunt-TVC combinations.

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